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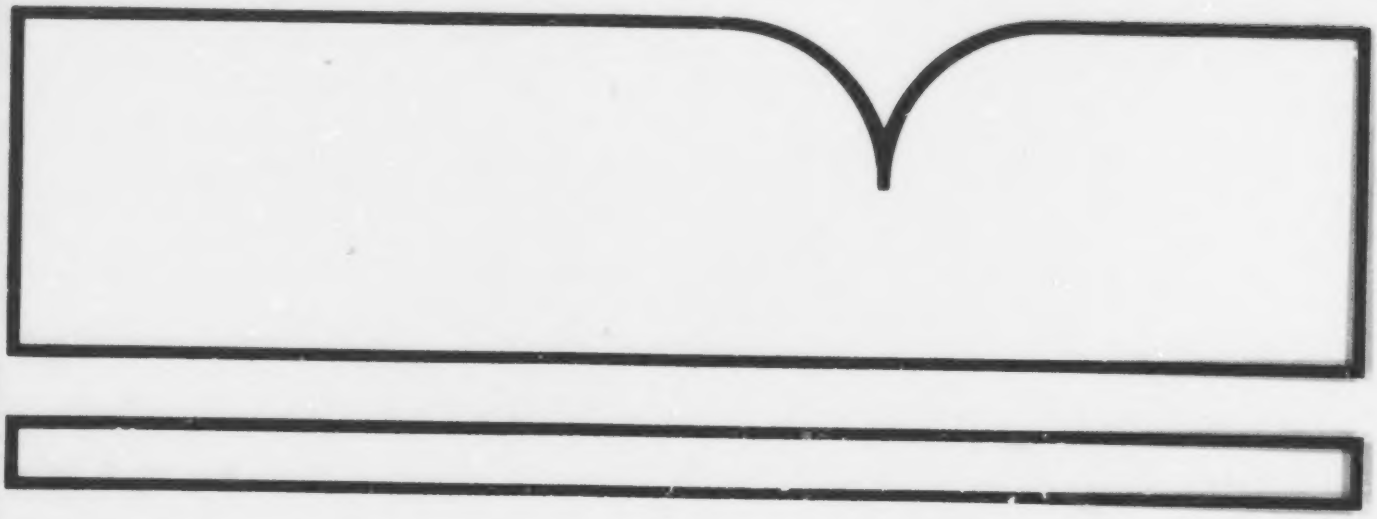

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# FIELD VALIDATION OF EXPOSURE ASSESSMENT MODELS
# VOLUME 2. ANALYSIS

by

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This is the second of two volumes describing a series of dual tracer experiments designed to evaluate the PAL-DS model, a Gaussian diffusion model modified to take into account settling and deposition, as well as three other deposition models. In this volume, an analysis of the data summarized in Volume 1 is given. The four models are described, and an evaluation of the performance of each is given. The evaluation is based on an analysis of $C_d/C_o$, the ratio of the crosswind-integrated concentrations of a depositing and nondepositing tracer, respectively, at a height of 1.5 m. The PAL-DS model is found to overestimate this ratio; a corrected source depletion model appears to give significantly better results. A novel method of determining the effective deposition velocity of the depositing tracer, based on a surface depletion approach, is described. A discussion of model sensitivities, experimental design, and the effects of measurement errors on the model evaluation is also given. Experimental uncertainties may well affect the performances of the models, but it is doubtful that their relative performances would be significantly changed. Errors in describing the diffusion meteorology are likely to be more important in predicting depleted concentrations than errors introduced by the choice of a particular deposition model, which are apt to be more systematic.



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# SECTION 1

# INTRODUCTION

This is the second of two volumes describing work performed on a project funded by the U. S. Environmental Protection Agency entitled "Field Validation of Exposure Assessment Models." The principal objective of this project was to evaluate the PAL model as modified for depositing pollutants. To that end a series of simultaneous depositing and nondepositing tracer releases were carried out, and the tracer concentrations were measured at five downwind sampling arcs. A description of the experimental procedures and a detailed summary of the results of this measurement program were given in the first volume of this report.

In this volume, an analysis of the collected data is given. The relative concentrations of depositing and nondepositing tracers are used to evaluate the deposition module of the PAL model as well as three other models that describe plume depletion. Descriptions of the models are provided, including input requirements in terms of micrometeorological and diffusion data. Their relative performances are assessed in light of the accuracy of the measurements and the sensitivities of the models to variations in the input parameters.

The basic approach used in evaluating the models is described, and the rationale for the particular experimental design that we adopted is discussed. The use of the surface depletion approach to obtain an appropriate estimate of the deposition velocity of the depositing tracer is explained. Several numerical experiments were performed to assess various aspects of the experimental design and the evaluation procedures and the results of these are also included.

# SECTION 2

# CONCLUSIONS

The PAL-DS model was found to overestimate consistently the amount of depositing pollutant at a height of 1.5 m. A corrected version of this model, which incorporates a modification that ensures conservation of mass, performed better, while a corrected source depletion model gave the best results of the four models tested. In all cases uncertainties in describing the diffusion meteorology are apt to be more important for estimating depleted air concentrations than differences arising from the choice of a particular deposition model. However, of the four models tested, the use of the corrected source depletion model appears to offer the best chance of avoiding systematic errors in the description of plume loss arising from deposition.

A new method for determining the effective deposition velocity for a depositing tracer, based on the surface depletion model of Horst (1977), gave results that appeared quite reasonable. A rigorous test of this approach was not possible, but numerical simulations of the deposition of a polydispersed tracer, combined with data from wind tunnel measurements, gave good agreement between observed and calculated deposition velocities.

Because a number of uncertainties in the tracer concentration measurements and their analyses may have adversely affected the model evaluations, statistical comparisons of model performance should be viewed with some caution. However, the relative performances of the four models seems unlikely to be seriously affected by these factors. Additional support for this conclusion is provided by the fact that the relative biases in the models' predictions are generally in keeping with numerical and physical analyses of their basic assumptions.

## SECTION 3

## RECOMMENDATIONS

Three additional tasks are suggested that would provide greatly increased confidence in model evaluations such as those just described and could result in better quantitative comparisons of models with each other or with theory. While relatively simple to state, each task is a major research effort in itself.

The first task is the development of a tracer generator capable of producing mono-dispersed or nearly mono-dispersed particles in the size range 1-5 μm diameter. The generator should be able to produce a quantity of material sufficient for ready detection at a range of 10 km or more. The tracer itself should be easily collected and analyzed. Such a tracer's size distribution could be more easily determined and non-isokinetic sampling effects could be estimated with better accuracy. Sample loss close to the source caused by the preferential depletion of larger size particles would be lessened, and the range of meteorological conditions in which the surface depletion method could be profitably used to determine deposition velocities would be increased.

The second task is a rigorous test of the surface depletion model of dry deposition, using this newly developed tracer technique. This task would involve a direct determination of the deposition velocity of a depositing tracer, e.g., by collecting material actually deposited on the ground, and the measurement of airborne concentrations of the depositing material close to the surface at a number of downwind arcs. These measurements could be done at relatively short distances from the tracer release point, on the order of 1 km or less.

The third task would be a more extensive evaluation of models such as the PAL-DS or corrected source depletion model. In particular, the distance to which concentration measurements are made should be increased to 10 km or more, in order to increase the range of values of plume loss that the models are to simulate. If a tracer generating technique such as that described above is used, substantial improvements in model evaluations should be possible.

## SECTION 4

## MODEL DESCRIPTIONS

The dual-tracer field measurements have been used to evaluate four Gaussian plume-depletion models: 1) the commonly used source depletion model, 2) a modified source depletion model that accounts for the alteration of the vertical concentration profile by deposition, 3) the PAL-DS model, which is a diffusion-deposition model based on a constant eddy-diffusivity solution of the advection-diffusion equation, and 4) a mass-conserving version of the PAL-DS model. These models are briefly described here, and the general characteristics of their predictions are discussed in relation to those of an exact model of plume depletion.

In the binormal Gaussian plume model, it is assumed that the horizontal and vertical pollutant distributions are independent of one another. As a consequence, our evaluation of plume depletion can consider simply the crosswind-integrated pollutant concentration. For a nondepositing pollutant, the Gaussian model gives

$$C_o(x,z,h) = Q_o\, D(x,z,h) = \frac{Q_o}{\sqrt{2\pi}\, u\sigma_z} \left\{ \exp\left[-(h-z)^2/\sigma_z^2\right] + \exp\left[-(h+z)^2/\sigma_z^2\right] \right\} . \quad (1)$$

Eq. (1) also defines a general diffusion function $D = C_o/Q_o$, which is useful in describing the plume depletion models. Here x and z are the downwind and vertical coordinates of the receptor, (x=0,z=h) is the location of the pollutant source, $C_o$ is the crosswind-integrated concentration, $Q_o$ is the pollutant release rate, and u is the mean wind speed. The vertical dimension of the plume, $\sigma_z$, is a function of downwind distance and atmospheric stability, ideally determined from measurement programs that used nondepositing tracers. Application of the Gaussian model to a depositing pollutant requires a modification to account for the reduction of airborne contamination, as well as to estimate the resulting surface contamination. However, because the Gaussian plume model

is based on empirical data and does not explicitly model the vertical diffusion process, it is not easy to make this modification in a way that is physically realistic.

Plume depletion has been commonly modeled with the Chamberlain (1953) source depletion technique, which accounts for loss of material from the plume by reducing the source strength as a function of downwind distance:

$$Q(x) = Q_o \exp\left[-\int_0^x v_d D(x',z,h)dx'\right] . \qquad (2)$$

Here the deposition flux to the surface is parameterized as a deposition velocity $v_d$ multiplied by the airborne pollutant concentration at some near-surface height $z_d$. The source depletion technique retains the Gaussian vertical concentration profile, and this distributes the dry deposition loss uniformly through the vertical extent of the plume. Since deposition actually depletes the portion of the plume adjacent to the surface, source depletion overestimates the ground-level concentration, overestimates the deposition, and underestimates the amount of material still airborne.

Horst (1977) developed a surface depletion model that provides an exact technique for modifying diffusion models to account for plume depletion. However, this model is computationally more complex and hence is often inappropriate for application with the Guassian plume diffusion model. The surface depletion model is described in the next section where it is used to determine the deposition velocity of the depositing tracer.

Horst (1980, 1983) has also developed a corrected source depletion model whose computational requirements are comparable to those of the source depletion model and whose predictions are in close agreement with those of the surface depletion model. In this approach, the nondepositing diffusion function $D(x,z,h)$ is modified by a profile correction factor $P(x,z)$ to account for the change in the vertical distribution caused by deposition

$$C_d(x,z,h) = Q(x)D(x,z,h)P(x,z) , \qquad (3)$$

where now

$$Q(x) = Q_o \exp\left[-\int_o^x v_d D(x',z_d,h) P(x',z_d) dx'\right] . \qquad (4)$$

The profile correction is determined by assuming that, within the near-surface layer depleted by deposition, the concentration profile is determined solely by the deposition flux to the surface and that the deposition flux is independent of height within that layer. The profile correction is

$$P(x,z) = \frac{1 + v_d R(z,z_d)}{1 + v_d \int_o^\infty u\, D(x,z',0)\, R(z',z_d) dz'} , \qquad (5)$$

where for a Gaussian plume the atmospheric resistance R is

$$R(z,z_d) = \sqrt{\frac{2}{\pi}}\, \frac{1}{u} \int_{z_d}^{z} \frac{dz'}{z'(d\sigma_z/dx)} . \qquad (6)$$

If the particle settling velocity w is an appreciable fraction of the deposition velocity, the term $v_d R$ in (5) must be modified (Horst, 1983). For the special case $wR \ll 1$, this may be approximated by replacing $v_d$ by $(v_d - w)$.

An alternative plume depletion model is based on the constant eddy-diffusivity solution of the advection-diffusion equation with a deposition boundary condition. The PAL-DS model is an example of such an approach. Ermak (1977) and Rao (1981) have suggested that this solution provides a framework for modifying the Gaussian plume model, to account for deposition, that is preferable to the source depletion model. This approach is attractive because the analytical solution is computationally inexpensive, and because it includes both deposition and settling. In order to match the predictions of the Gaussian plume model for the case of a nondepositing pollutant, the analytical solution is modified by making the substitution $2Kx/u = \sigma_z^2$. Note that this procedure is strictly correct only for the case where $\sigma_z$ varies as $x^{\frac{1}{2}}$. The resulting expression for the crosswind-integrated concentration is then

$$C_d(x,z,h) = \frac{Q_o}{\sqrt{2\pi}\, u\sigma_z} \exp\left[-\frac{w(z-h)x}{u\,\sigma_z^2} - \frac{w^2 x^2}{2u^2\sigma_z^2}\right]\left\{\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\left(1 - 2\sqrt{2\pi}\,\frac{Vx}{u\sigma_z}\exp\xi\,\operatorname{erfc}\xi\right)\right\} \qquad (7)$$

where

$$V = v_d - w/2 \ ,$$

$$\xi = \frac{(z+h)}{\sqrt{2}\,\sigma_z} + \sqrt{2}\,\frac{Vx}{u\sigma_z} \ .$$

The PAL-DS or K model has been evaluated (Horst, 1984) by comparing its predictions for nonsettling pollutants to those of the surface depletion model. For $\sigma_z$ proportional to $x^{\frac{1}{2}}$ the surface depletion and PAL-DS models give identical results. However with physically realistic $\sigma_z$'s, i.e., Briggs' empirical formulas for rural dispersion (Gifford, 1976), the comparison is less satisfactory. For an unstable atmosphere the comparison is poor because Briggs' $\sigma_z$ is linear in x for all x. In this case the PAL-DS model overpredicts the ground-level contamination $C_d(z=0)$ and the source depletion model agrees better with the surface depletion model. For neutral and stable atmospheric conditions the PAL-DS model still overpredicts $C_d(z=0)$, but its predictions fall between those of the source and surface depletion models.

One reason for these differences is that the PAL-DS model does not conserve mass with a general functional form for $\sigma_z(x)$. This can be corrected by dividing $C_d(x,z)$, as predicted with Eq. (7), by the horizontal flux calculated from Eq. (7) and then multiplying the result by the actual horizontal flux determined via the deposition loss:

$$C_m(x,z) = \frac{C_d(x,z)}{\int_0^\infty u\, C_d(x,z')dz'}\left[Q_o - \int_0^x v_d C_m(x',z_d)dx'\right] \ . \qquad (8)$$

Here $C_d$ refers to the pollutant concentration predicted by Eq. (7) and

$C_m$ denotes the pollutant concentration with mass conservation. Rao (1981) provides analytical expressions for the vertical integral of $C_d(x,z)$. By forcing the PAL-DS model to conserve mass, its predictions are noticeably improved, particularly for large deposition velocities and for unstable atmospheres.

## SECTION 5

## DETERMINATION OF INPUT PARAMETERS FOR MODELS

In this section we outline the methods used to determine the various input parameters required for the evaluation of the models to be evaluated. The procedures used are not always intuitively obvious and are subject to some uncertainties arising from the data, its interpretation, and various assumptions that must be made. A full treatment of these uncertainties and the models' sensitivities to them is given in Section 8.

Since the prime purpose of this project was to evaluate plume depletion models, it was necessary to obtain a dependable estimate for the deposition velocity. The literature is rife with estimates of $v_d$ ranging over many orders of magnitude (Sehmel, 1980), and the situation was not helped by the uncertainties in the size distribution of zinc sulfide (ZnS) tracer. The approach adopted to address this problem was based on the surface depletion model for calculating plume deposition (Horst, 1977, 1983). The surface depletion model is a modification of nondepositing plume models that incorporates the deposition boundary condition in an exact manner. The model represents the crosswind-integrated depletion at location x' as a negative, ground-level source with a strength per unit downwind distance equal to the deposition flux $v_d C_d(x',z_d,h)$. The depletion of the crosswind-integrated tracer concentration at location (x,z), caused by deposition at the upwind location (x',z=0), is determined by the diffusion of that loss over the distance (x-x',z). The total depletion at (x,z) is then found by integrating over all deposition upwind of x,

$$C_o(x,z,h) - C_d(x,z,h) =$$

$$\int_0^x v_d C_d(x',z_d,h)\ D(x-x',z,h=0)dx' \ . \qquad (9)$$

The diffusion function D can be determined experimentally by releasing a second nondepositing tracer at ground level, h = 0; i.e.,

$$D(x,z,h=0) = (1/Q_o)C_o(x,z,h=0) \quad . \tag{10}$$

Substituting Eq. (10) into Eq. (9), evaluating the depletion at $z=z_d$, and solving for the effective deposition velocity $\overline{v}_d$ gives

$$\overline{v}_d = \frac{\int_o^x v_d(x')C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'}{\int_o^x C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'}$$

$$= \frac{C_o(x,z_d,h) - C_d(x,z_d,h)}{\int_o^x C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'} \quad . \tag{11}$$

This method has the major advantage that only near-surface sampling is required, in contrast to other methods discussed by Horst et al., (1983). For elevated releases, three tracers are needed because non-depositing tracers are required both at the source height of the depositing tracer and at ground level. The release at the source height is required to measure the depletion at distance x in the numerator of Eq. (11), and the release at ground level is required to determine the diffusion of the deposition losses in the denominator. If the release height is small, as was the case for our experiments, one nondepositing tracer will suffice. The effective deposition velocity obtained by measuring $C_D$ and $C_0$ and applying Eq. (11), can then be used in each of the four models described in Section 4.

An examination of the PAD-DS model solution in Equation 7 shows that the crosswind integrated concentration of tracer is also determined by the mean wind speed u, the vertical dispersion $\sigma_z$, the release height h and the settling velocity, $v_s$. The vertical dispersion parameter $\sigma_z$ was determined from the crosswind integrated concentrations of the sulfur hexafluoride ($SF_6$), assuming that the vertical dispersion was described by a Gaussian profile, as also assumed in the PAL-DS model. As noted in Section 8, there is evidence that this assumption is not true, but the predictions are not sensitive to the value of $\sigma_z$. Instead, the product,

$u\sigma_z$ is important, as can be seen from an examination of Eq. 7. The mean wind speed u was evaluated iteratively at a height of 0.53 $\sigma_z$, using the wind data collected on the 61 m tower at the 1600-m arc. The settling velocity to be ascribed to the depositing tracer is a function of the size distribution and the distance from the release point. We chose a value of 0.5 cm/s as a representative average to use in the model calculations. A discussion of this choice is also given in Section 8.

## SECTION 6

## DATA ANALYSIS

The data collected for this project have been tabulated and displayed in the first volume of this report. For comparisons of predicted and actual results, we concluded that the crosswind-integrated concentration of the tracer at one height was the most appropriate quantity to examine. The use of the crosswind-integrated value, instead of values at each azimuth, has several advantages. First, it is intrinsically a smoother variable, as it integrates over a collection of samplers and is thus less susceptible to minor variations in sampler performance. It also avoids difficulties associated with the non-Gaussian nature of the crosswind distribution of concentration. In several of our releases, the tracer distributions were bimodal or skewed, and a Gaussian fit to the distributions would have been inappropriate. In addition, the principal interest in this project is the testing of plume depletion models, and the crosswind-integrated plume loss at a given height is a good measure of this performance.

The crosswind integrated concentrations were calculated using a simple trapezoidal integration of the tracer concentrations at each azimuth. In practice, there were a variety of approximations that had to be made, depending on the quality and completeness of the data at each arc. If the plume shape was well defined by both the ZnS and $SF_6$ concentrations, then the integration for each was carried out using values at all of the samplers. If one tracer gave fairly complete crosswind definition and the second did not, the crosswind concentration was first computed for the tracer with the more complete arc. Then, an arc sector was selected in which both tracers exhibited reliable results, the integrated concentrations in this sector were computed for both tracers, and the ratio between the two was found. This ratio was then used to compute the crosswind-integrated value for the second tracer. In general, the $SF_6$ tracer provided the better definition for the complete crosswind-integrated concentrations, but there were some exceptions. As an example of this procedure, consider the data for June 27, 1983 at the 100-m arc. The loss of two gasoline engines resulted in missing ZnS data at the north end of

the arc. Hence, the ratio of the crosswind-integrated concentrations south of 100° was determined, and this ratio was multiplied by the total crosswind-integrated concentration of $SF_6$ to obtain the ZnS integrated value. For the case of May 18, 1983, the ratio at 100 m was obtained simply by averaging the ratios of ZnS to $SF_6$ at 4 azimuths, since it appeared that the $SF_6$ peak was not resolved by the coarse spacing of the $SF_6$ samplers. Finally, in the run of June 24, 1983 the plume drifted off the arc. An extrapolated Gaussian fit to the $SF_6$ data was judged to fit the measured values fairly well, and this fit was used to estimate the $SF_6$ crosswind integrated concentrations. The ZnS values were then obtained by the scaling procedure described above. Table 1 has a summary of the crosswind integrated concentrations at z = 1.5 m obtained for each arc, the ratio of crosswind integrated concentrations of ZnS and $SF_6$, and the range of azimuths used to evaluate the ratio.

Table 2 summarizes the values of $\sigma_z$, u at 0.53 $\sigma_z$ and the deposition velocities determined at 1600 m and 3200 m from the concentration data. Values for $\bar{v}_d$ are also given at 800 m. These were set equal to 1.06 times the value at 1600 m; the factor of 1.06 was determined from numerical simulations, using the PAL-DS model, of the variation of $\bar{v}_d$ as a function of distance. It was felt that this value was likely to be more accurate than a determination of $v_d$ from the data using only 3 arcs. A further discussion is given in the next section.

TABLE 1. CROSSWIND INTEGRATED CONCENTRATIONS (CWICs) OF ZnS AND $SF_6$, RATIOS OF CWICs AND AZIMUTH RANGE USED TO OBTAIN RATIOS IN SIX DUAL TRACER RELEASES

| Date | Arc (m) | ZnS CWIC ($s/m^3$) | $SF_6$ CWIC ($s/m^3$) | Ratio | Azimuth Range (deg) |
|---|---|---|---|---|---|
| 5/18/83 | 100 | .0132 | .0195 | 0.68 | 116-140 |
| | 200 | .00647 | .0117 | 0.55 | all[a] |
| | 800 | .00224 | .00373 | 0.60 | 120-128,132-140 |
| | 1600 | .000982 | .00214 | 0.46 | all |
| | 3200 | .000586 | .00130 | 0.45 | 128-134 |
| 5/26/83 | 100 | .0389 | .0519 | 0.75 | 92-116,124-132 |
| | 200 | .0224 | .0367 | 0.61 | 90-118 |
| | 800 | .00747 | .0129 | 0.58 | all |
| | 1600 | .00325 | .00908 | 0.36 | all |
| | 3200 | .00231 | .00722 | 0.32 | 107-110,116-125 |
| 6/5/83 | 100 | .0217 | .0271 | 0.80 | all |
| | 200 | .0116 | .0181 | 0.64 | all |
| | 800 | .00306 | .00591 | 0.52 | all |
| | 1600 | .00132 | .00331 | 0.40 | all |
| | 3200 | .000662 | .00179 | 0.37 | 107-112[b] |
| 6/12/83 | 100 | .0409 | .0918 | 0.45 | all |
| | 200 | .0272 | .0486 | 0.56 | 86-102,110-120 |
| | 800 | .00804 | .0201 | 0.40 | 104-116 |
| | 1600 | .00426 | .0131 | 0.33 | all |
| | 3200 | .00314 | .00915 | 0.34 | all[c] |
| 6/24/83 | 100 | .0539 | .0839 | 0.64 | all[d] |
| | 200 | .0310 | .0424 | 0.73 | all[d] |
| | 800 | .00525 | .0105 | 0.50 | all[d] |
| | 1600 | .00338 | .00861 | 0.39 | all[d] |
| | 3200 | .00292 | .00664 | 0.44 | all[d] |
| 6/27/83 | 100 | .0643 | .0884 | 0.73 | 100-132 |
| | 200 | .0289 | .0611 | 0.47 | all |
| | 800 | .00723 | .0134 | 0.54 | 76-120 |
| | 1600 | .00252 | .00615 | 0.41 | 86-112 |
| | 3200 | .00125 | .00311 | 0.40 | all[e] |

[a] All implies using all above background data, not necessarily all samplers in an arc.
[b] $SF_6$ values linearly interpolated in range 107-112 degrees.
[c] Value of $SF_6$ at 11 degrees set equal (guess based on ZnS shape) to $SF_6$ value at 107 degrees; ZnS values at 104, 105 and 106 degrees linearly interpolated between 103 and 107 degrees.
[d] $SF_6$ CWICs obtained from Gaussian fits to data at 100, 200, 1600 and 3200 m.
[e] $SF_6$ values at 101 and 110 degrees linearly interpolated.

TABLE 2. DEPOSITION VELOCITIES, u, AND $\sigma_z$ FOR SIX TRACER RELEASES

| Date | Arc (m) | $u(z=0.53\sigma_z)$ (m/s) | $\sigma_z$ (m) | $\bar{v}_d$ (cm/s) |
|---|---|---|---|---|
| 5/18/83 | 100 | 5.26 | 7.35 | -- |
| | 200 | 6.03 | 11.03 | -- |
| | 800 | 7.61 | 27.99 | 4.21 |
| | 1600 | 8.53 | 43.36 | 4.05 |
| | 3200 | 9.43 | 65.02 | 3.65 |
| 5/26/83 | 100 | 2.11 | 6.81 | -- |
| | 200 | 2.37 | 8.80 | -- |
| | 800 | 3.23 | 18.96 | 1.93 |
| | 1600 | 3.59 | 24.34 | 1.80 |
| | 3200 | 3.83 | 28.72 | 1.74 |
| 6/5/83 | 100 | 3.28 | 8.62 | -- |
| | 200 | 3.66 | 11.79 | -- |
| | 800 | 4.74 | 28.36 | 3.14 |
| | 1600 | 5.40 | 44.59 | 3.02 |
| | 3200 | 6.32 | 70.46 | 2.84 |
| 6/12/83 | 100 | 1.74 | 4.26 | -- |
| | 200 | 2.29 | 6.71 | -- |
| | 800 | 3.00 | 13.00 | 1.75 |
| | 1600 | 3.39 | 17.79 | 1.62 |
| | 3200 | 3.75 | 23.11 | 1.31 |
| 6/24/83 | 100 | 1.67 | 5.08 | -- |
| | 200 | 2.12 | 8.50 | -- |
| | 800 | 3.07 | 24.59 | 1.56 |
| | 1600 | 3.24 | 28.50 | 1.47 |
| | 3200 | 3.46 | 34.61 | 1.14 |
| 6/27/83 | 100 | 1.80 | 4.30 | -- |
| | 200 | 2.12 | 5.59 | -- |
| | 800 | 3.17 | 18.61 | 1.17 |
| | 1600 | 3.80 | 34.08 | 1.15 |
| | 3200 | 4.37 | 58.71 | 1.10 |

## SECTION 7

## MODEL EVALUATION

The output of the the PAL-DS model is a three-dimensional field of tracer concentrations. Measuring such a field in its entirety is clearly impossible, and some compromise is required. Moreover, the model output depends on a number of factors, which may be roughly divided into two classes: those describing the diffusion meteorology and those describing the deposition. In reality the two sets of factors are related, but the diffusion aspects of various models have been evaluated extensively in a host of studies (e.g., Irwin, 1983). There appears to be little point in emphasizing such analyses for our limited data set; instead, we focus on the deposition part of the model. (In Section 9 we briefly summarize comparisons of the observed diffusion characteristics with some current formulations of the "expected" behavior.) To evaluate the model's performance, we assume that the diffusion meteorology is known or can be determined. What remains, then, is to evaluate how well the model describes the depletion in the plume arising from deposition and settling. As noted earlier, we chose to employ a dual tracer technique for this exercise. The nondepositing tracer was $SF_6$, while ZnS was the depositing tracer. Differences in $SF_6$ and ZnS concentrations may be assumed to arise from the removal of depositing tracer at the surface, and the model description of this process may thereby be evaluated. Thus, the basic quantity to be discussed is the ratio $C_d/C_o$, where $C_d$ is the crosswind-integrated concentration of depositing tracer 1.5 m above the surface and $C_o$ is a similar crosswind-integrated concentration of non-depositing tracer. In practice it was most convenient to measure concentrations of both tracers at some height close to the surface (1.5 m), where $C_d$-$C_o$ is largest, rather than over an extended vertical extent.

The predictions of four models were evaluated: the PAL-DS model, the PAL-DS model corrected to ensure mass conservation, the source depletion model proposed by Chamberlain and the source depletion model corrected by the inclusion of a profile factor to modify the vertical distribution. These were described in Section 4. Comparisons of the predicted and

measured values of $C_d/C_o$ are shown in Figures 1-4. The calculated ratios of $C_d/C_o$ were determined by using $\bar{v}_d$, the effective deposition velocities [of Eq. (1)] in each of the four models, for all six dual-tracer releases. Results for the 800-, 1600-, and 3200-m arcs are shown. The observed ratios are those actually measured in the field tests. The PAL-DS model shows the largest differences between observed and calculated values, while the corrected source depletion model shows the best agreement. The performance of the four plume depletion models relative to the data also agrees qualitatively with previous analyses of Horst (1984). The uncorrected source depletion model distributes the effect of deposition uniformly through the vertical extent of the plume, rather than preferentially depleting the plume at ground level, and thus overestimates the near-surface concentration ratio. Much better results are given by the corrected source depletion model, which accounts for the change in the vertical distribution caused by deposition.

The PAL-DS model uses an empirical value for $\sigma_z$ at the receptor, but assumes that $\sigma_z$ upwind of the receptor varies as $x^{\frac{1}{2}}$. Since $\sigma_z$ is more nearly a linear function of x near the source, this assumption overestimates $\sigma_z$ upwind of the receptor, underestimates the near-surface airborne contamination and the deposition upwind of the receptor, and thus overestimates the near-surface concentration ratio $C_d/C_o$ at the receptor. Part of this error is corrected by forcing the model to conserve mass. However, $C_d/C_o$ is still overestimated, because overestimation of $\sigma_z$ upwind of the receptor also causes the deposition losses to be mixed through a vertical depth that is too large. The superior performance of the corrected source depletion model is in keeping with previous analyses of Horst (1984).

Fox (1981) has summarized recommendations of the American Meteorological Society Workshop on Dispersion Model Performance and listed a number of statistical quantities that characterize the agreement between model predictions and observations.

These include the mean bias $\bar{d}$,

$$\bar{d} = \sum_{i=1}^{N} d_i/N \tag{12}$$

where $d_i$ is the difference between observed ($O_i$) and predicted ($P_i$) values, the variance $S^2$,

$$S^2 = \sum_{i=1}^{N} (d_i-\bar{d})^2/(N-1), \tag{13}$$

and the mean square error (MSE)

$$MSE = \sum_{i=1}^{N} d_i^2/N \ . \tag{14}$$

Fox (1981) also noted that the correlation coefficient, r, was a useful indicator of model performance. Irwin (1983) and others have used the fractional error E, and its standard deviation $\sigma_E$, where E is defined by

$$E = 2 \sum_{i=1}^{N} \left[ ((P_i-O_i)/(P_i+O_i) \ /N \right]. \tag{15}$$

Willmott (1982) took some exception to the recommendations of Fox (1981), and suggested additional or alternative measures of model performance, including the mean absolute error, MAE, where

$$MAE = \sum_{i=1}^{N} |P_i - O_i|/N \ , \tag{16}$$

and the index of agreement, I,

$$I = 1 - \sum_{i=1}^{N}(P_i'-O_i')^2 / \sum_{i=1}^{N}(|P_i'| + |O_i'|)^2 \qquad (17)$$

where $P_i' = P_i - \bar{O}$ and $O_i' = O_i - \bar{O}$.

For our analysis, we chose the ratio of the crosswind-integrated concentrations, $C_d/C_o$, for our basic variable (either $P_i$ or $O_i$). Table 3 provides a compilation of all of the statistical measures of model performance, for six dual-tracer releases and using results from the 800-, 1600-, and 3200-m arcs. Hence, N = 18 in Eqs. (12)-(17).

TABLE 3. STATISTICAL MEASURES OF MODEL PERFORMANCE

| Parameter/Model | PAL-DS | Corr. PAL-DS | Source Dep. | Corr. Source Dep. |
|---|---|---|---|---|
| Mean bias | 0.21 | 0.07 | 0.11 | 0.01 |
| Variance | 0.007 | 0.003 | 0.002 | 0.004 |
| Mean square error | 0.052 | 0.007 | 0.014 | 0.004 |
| Correlation coeff. | 0.63 | 0.79 | 0.82 | 0.70 |
| Fractional error | 0.39 | 0.15 | 0.23 | 0.03 |
| $\sigma_E$ | 0.14 | 0.11 | 0.10 | 0.13 |
| Mean absolute error | 0.21 | 0.07 | 0.11 | 0.05 |
| Index of agreement | 0.42 | 0.76 | 0.64 | 0.83 |

Although the corrected source depletion model works best in the mean, the deviations S from the mean bias are similar for all models and the corrected source depletion model does not seem to be as well correlated with the observations as some of the other models. A likely cause for the latter is that the corrected source depletion model is more sensitive than the other models to the value of $\sigma_z$, and this parameter is somewhat

uncertain because it was not measured directly. All of the models depend principally on the product $u\sigma_z$ and not on their individual values, and beyond 100 m downwind distance, $u\sigma_z$ is simply inversely proportional to the measured crosswind-integrated $SF_6$ concentration. However the predictions of the corrected source depletion model are also a function of $P(x,z_d)$, Equation 5, and the integrand in the denominator of P includes the product uR, which depends on $(d\sigma_z/dx)^{-1}$.

We noted that in this table and in Figures 1-4 we have limited our comparisons to the results from the 800-, 1600- and 3200-m arcs. At the 100- and 200-m arcs the effective deposition velocity is expected to change more rapidly with distance, and our confidence in the determination of $\overline{v}_d$ is less. However, we have carried out a similar statistical comparison using results from all 5 arcs, deposition velocities estimated from the 1600 m values, and model calculations of the changes of $\overline{v}_d$ with distance. Despite the greater uncertainties in the input values, the relative performances of the models were essentially unchanged. The uncorrected PAL-DS model still showed the worst bias, and the corrected source depletion model again gave the best agreement in the mean.

We noted above that the 800-m deposition velocities were obtained by scaling the 1600-m values with factors estimated from PAL-DS model simulations. These simulations indicate that $\overline{v}_d$ (800 m) should be about 6% higher than $\overline{v}_d$ (1600 m). We also obtained values of $\overline{v}_d$ (800 m) by evaluating the convolution integral in Eq. (11), and found that $\overline{v}_d$ (800 m)/$\overline{v}_d$ (1600 m) averaged 0.86 with a standard deviation of 0.12. This seems odd, since the removal of larger particles close to the release point should result in a decrease of $\overline{v}_d$ with distance. In view of this "unphysical" result, we chose to use the scaled values for $\overline{v}_d$ (800 m) in our principal model evaluations. However, we carried out the same statistical tests described above using the measured $\overline{v}_d$ (800 m) values instead of the scaled ones. The relative behavior of the models was again similar to that already described.

A possible source of the odd behavior at the 800-m arc is as follows. The depletion integral in the denominator of (11) was evaluated by using a logarithmic interpolation of the tracer concentrations between the

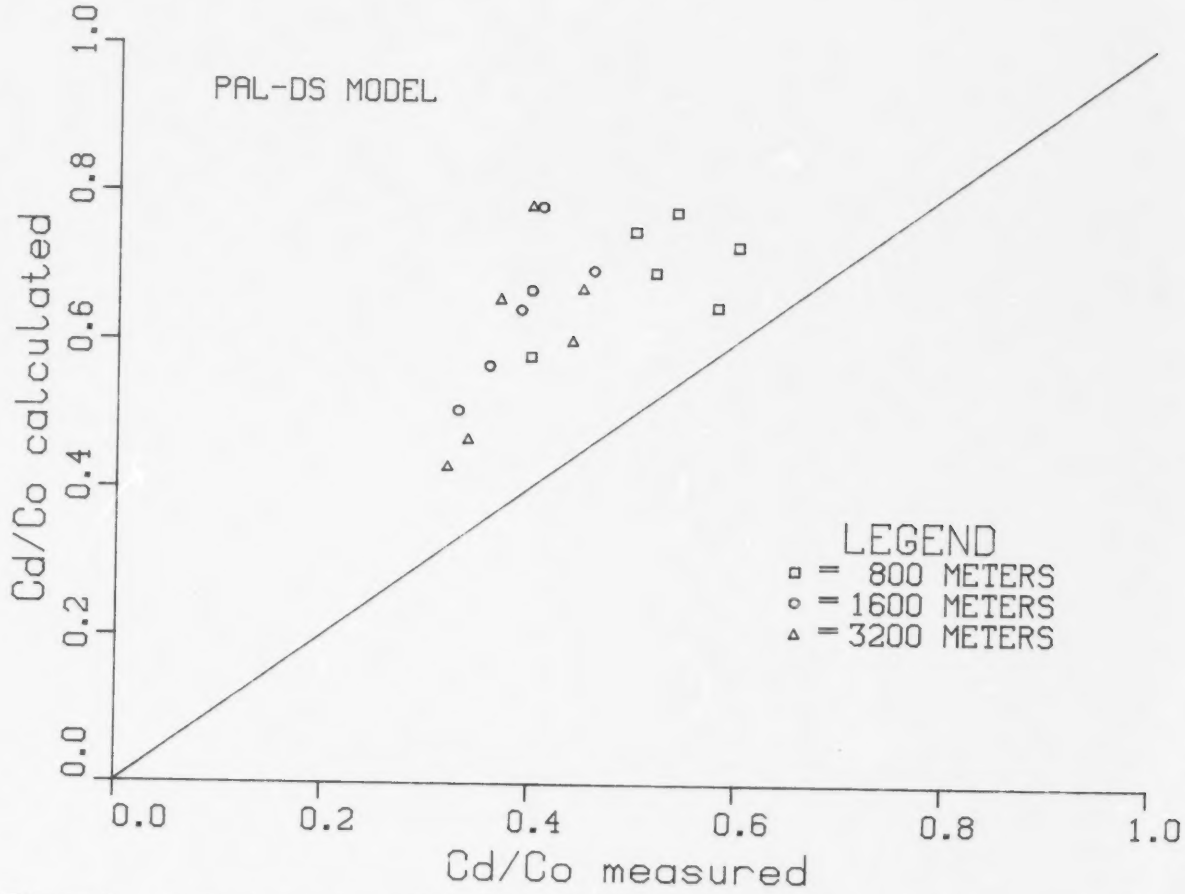


Figure 1. Comparison of predicted and measured concentration ratios for PAL-DS model. Straight line indicates perfect agreement.

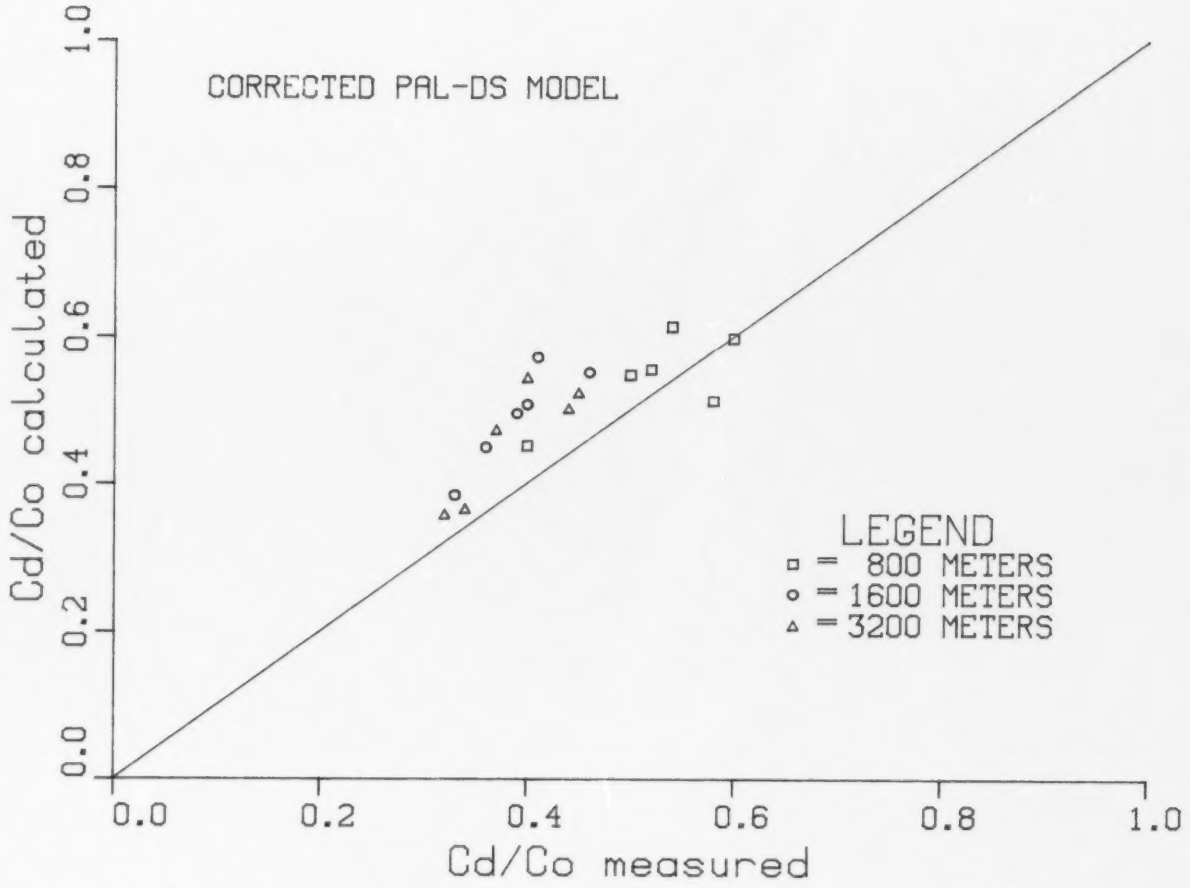


Figure 2. Comparison of predicted and measured concentration ratios for corrected PAL-DS model. Straight line indicates perfect agreement.

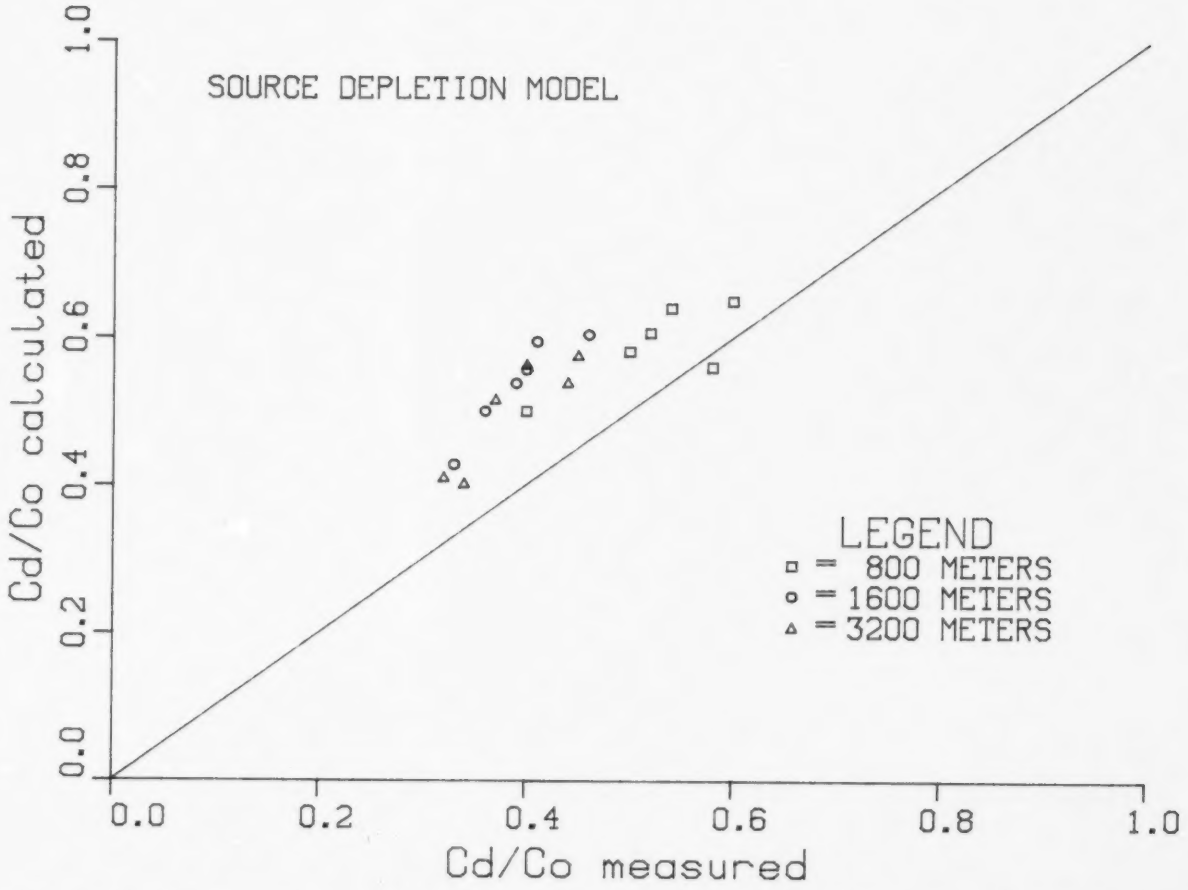


Figure 3. Comparison of predicted and measured concentration ratios for source depletion model. Straight line indicates perfect agreement.

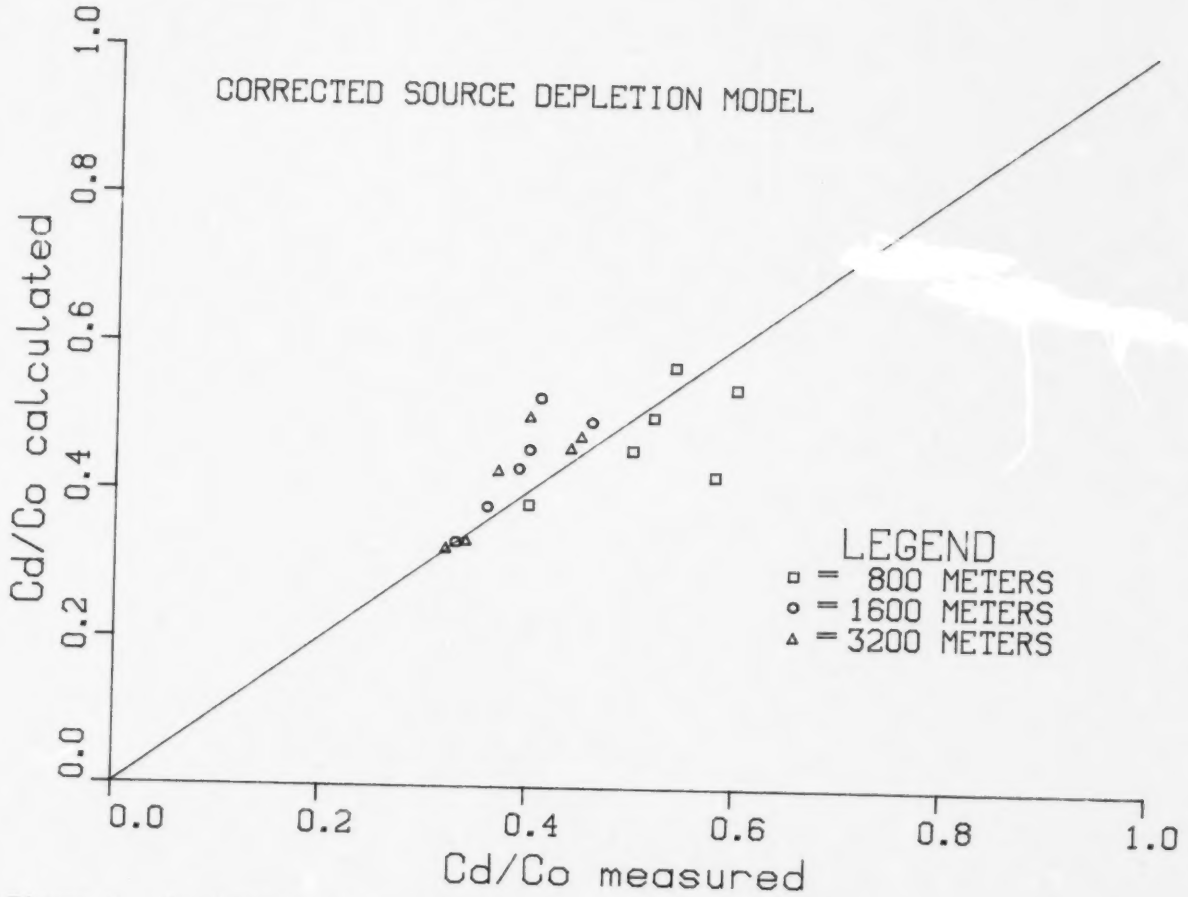


Figure 4. Comparison of predicted and measured concentration ratios for corrected source depletion model. Straight line indicates perfect agreement.

measurement arcs. For distances less that 100 m, Co(h=0) was estimated with the Gaussian plume formula (1), using a linear interpolation of $\sigma_z$ from its observed value at 100 m to a value of zero at the release point. $C_d$ was estimated in this region by reducing the estimated $C_o$(h=2m) by a depletion factor which varied logarithmically with distance from a value of 1 at the distance where the plume "first reaches" the surface (where $\sigma_z$=h) to the observed value of $C_d/C_o$ at 100 m. Since the release height of the depositing tracer is near the surface, the first and last 100 m contribute 35-45% of the depletion integral at 1600 and 3200 m, and thus inadequacies in this extrapolation procedure might cause an error of 5-10% in the calculated deposition velocity, However, for distances less than 1600 m, any inadequacies would be more significant and might even lead to "unphysical" results.

## SECTION 8

## RESTRICTIONS AND SENSITIVITIES

In assessing the relative performance of models it is useful to consider the effects of various uncertainties in the data and its evaluation. There are three principal areas to consider: 1) the sensitivity of the model to variations in the input parameters, 2) the adequacy of the experimental design, and 3) the accuracy to which the measured concentrations can be determined. We now turn to a discussion of each of these areas.

### SENSITIVITY OF MODELS TO VARIATIONS IN INPUT PARAMETERS

A number of factors can affect the predictions of the various plume depletion models, and the effects can vary from model to model. While it is impractical to review the behavior of each model in full detail, it is useful to consider their sensitivity to some of the more important input parameters. Fortunately, the models are relatively robust in their behavior, making it possible to draw a number of useful conclusions about their performance even in the presence of some uncertainties in these parameters.

The most obvious variable to consider is the value of the deposition velocity itself. Figures 5 and 6 show the variation of $C_d/C_o$ as a function of downwind distance for two different combinations of stability and wind speed, a settling velocity of 0.5 cm/s and a range of deposition velocities, as predicted by the PAL-DS model, for a release height of 2 m. The two stability categories correspond to the two extremes that were encountered during the course of our field tests. The first case shown had the largest values of L, the Monin-Obukhov length, while the second showed the smallest L. The range of deposition velocities encompasses the range of values found from our field measurements.

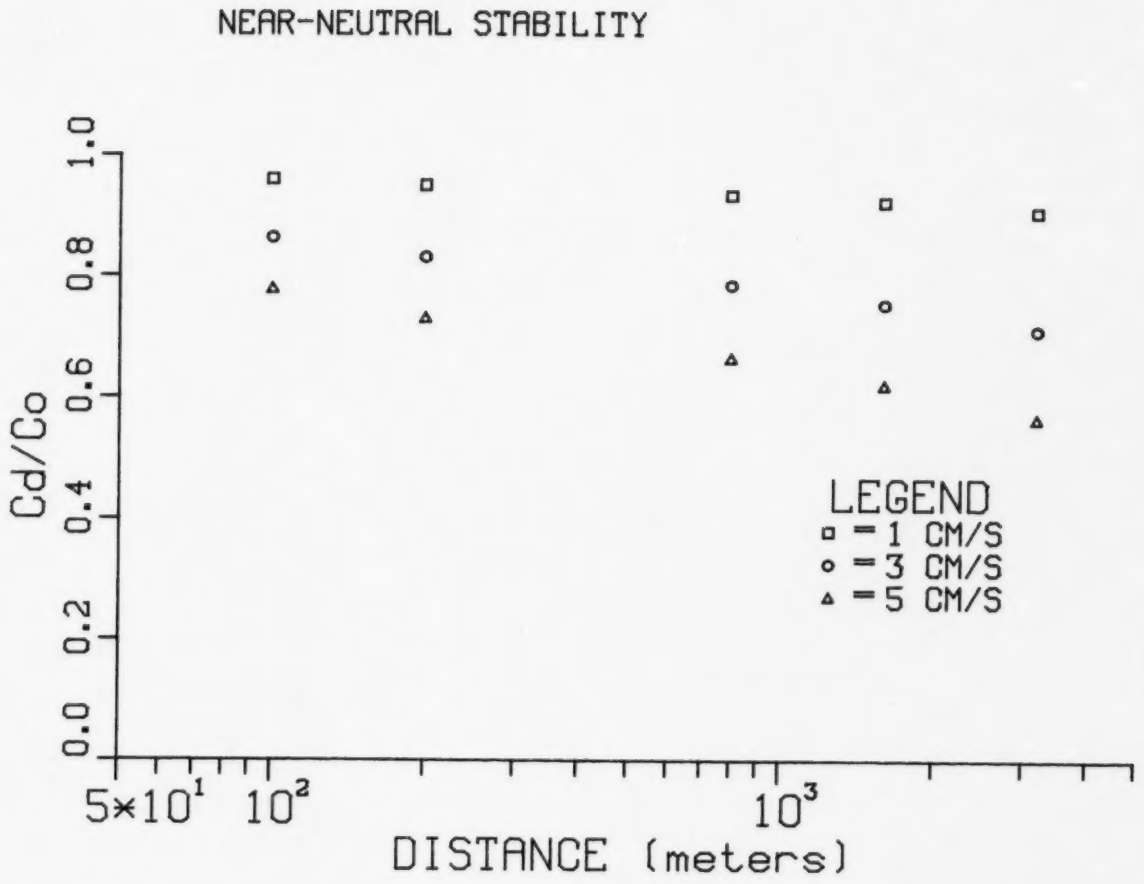


Figure 5. Dependence of concentration ratios on distance for near-neutral stability.

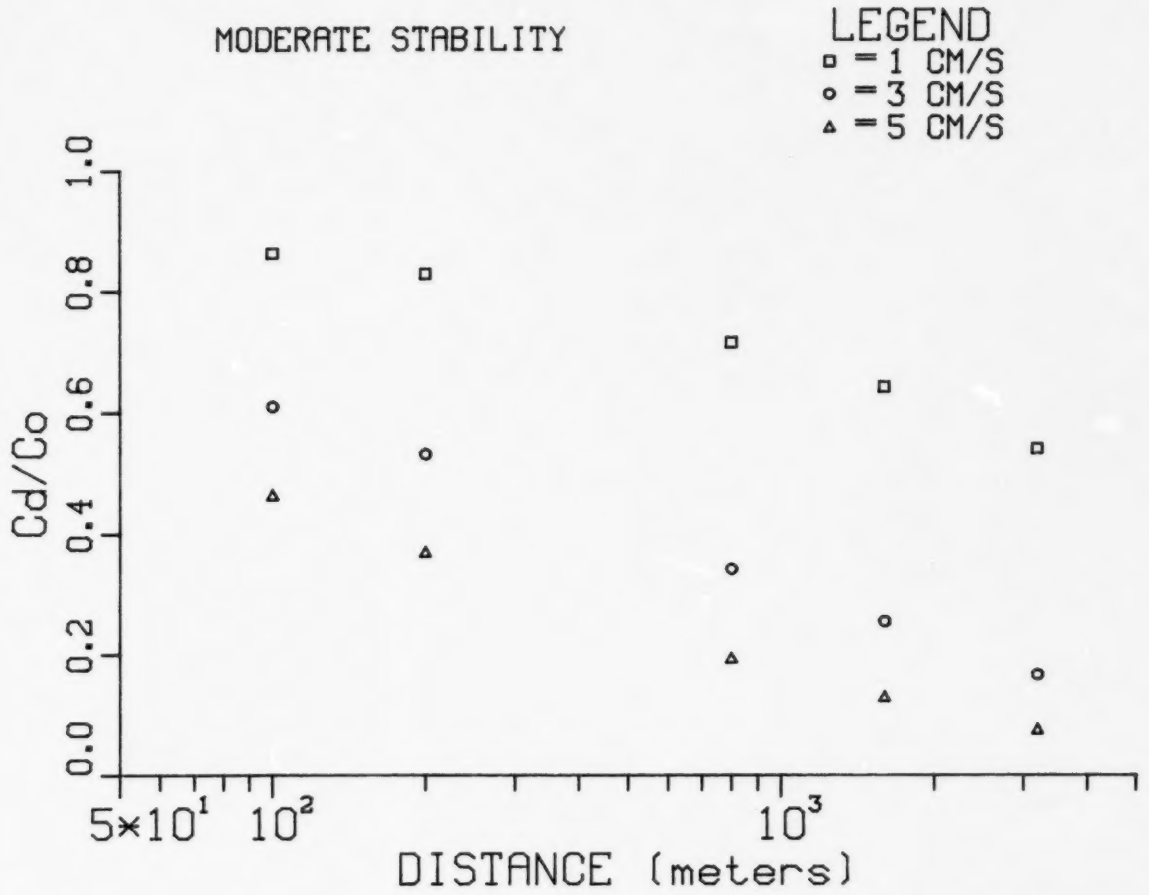


Figure 6. Dependence of concentration ratios on distance for moderate stability.

The sensitivity of the PAL model to deposition velocity is seen to be a strong function of stability, and the range of deposition velocities that a tracer may exhibit also depends on the stability. Figure 7 shows the relationship between observed and predicted concentration ratios for the corrected source depletion model, when the deposition velocity is allowed to range from 0.75 $\bar{v}_d$ to 1.25 $\bar{v}_d$, where $\bar{v}_d$ is the measured value. The sensitivities of the other models are comparable. It appears that a 25% change in the value of the deposition velocity that is used as an input parameter in the models might be sufficient to change our conclusions about the relative performances of the models. For example, if the deposition velocities were all increased by 25%, the PAL-DS model predictions would cluster more closely about the 1:1 line of perfect agreement in Figure 1, while the corrected source depletion model predictions would be too low. This may seem somewhat disturbing, since an accuracy of 25% in measurements of $\bar{v}_d$ for particles would normally be considered exceptionally good under the best of circumstances, and our experimental conditions should not be confused with such circumstances. However, there is a "self-correcting" aspect to this issue that alleviates this pessimism to some extent. We shall consider this in the last part of this section, when we discuss the accuracy of our measurements.

As noted earlier, the PAL-DS model also requires a value for the mean wind speed, u, and the vertical dispersion parameter $\sigma_z$. Except for some limited tower data at the 1600 m arc, no measurements of the vertical variation of the tracer concentrations were made, and even at the 1600 m arc the sampling did not extend above 25 m. Hence, direct determinations of $\sigma_z$ as a function of x were not possible. A second difficulty is the choice of mean wind speed. The Gaussian model implicitly assumes a wind speed that is constant with height, but it is apparent that the mean speed at which a plume from a ground source is transported will not be constant with downwind distance, especially near the source. Instead, as the plume's vertical spread increases, the effective transport speed increases.

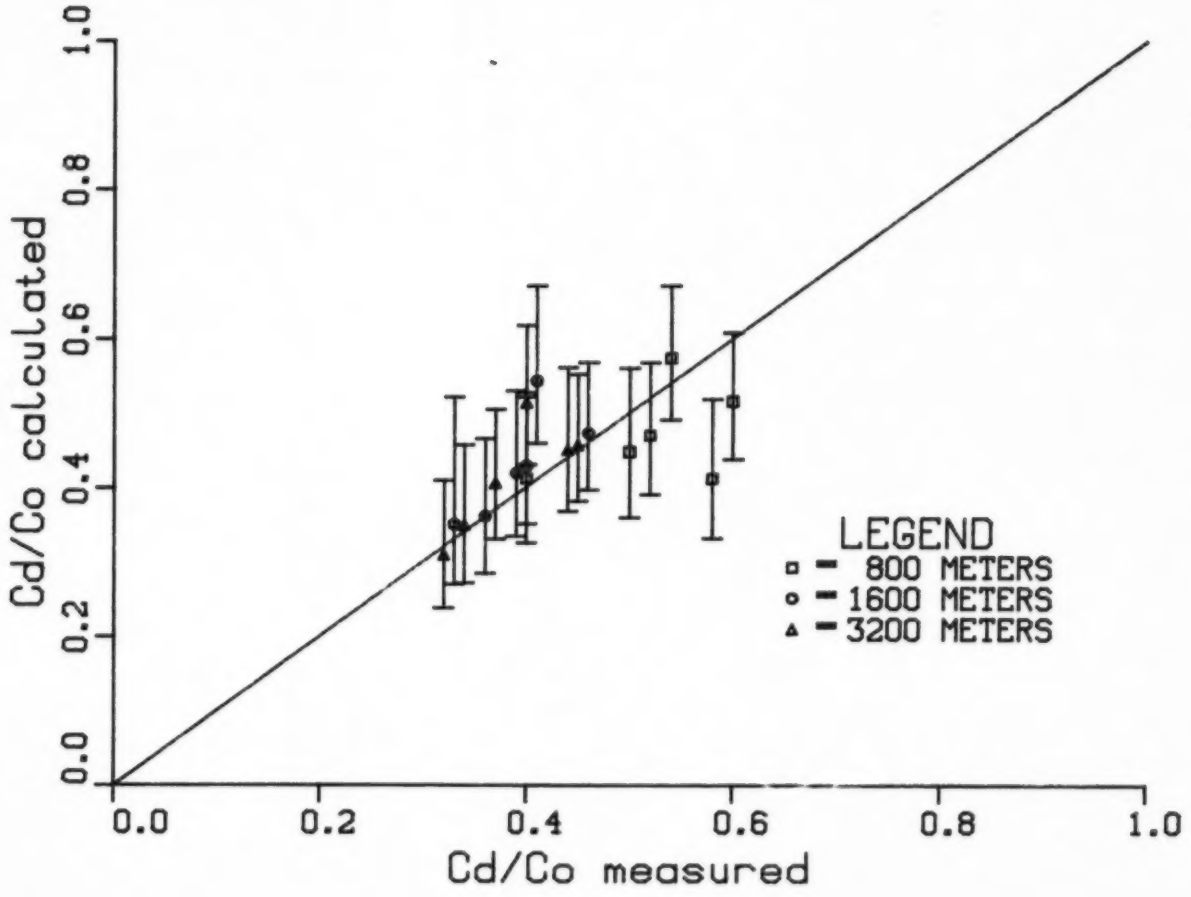


Figure 7. Sensitivity of concentration ratios to deposition velocity for corrected source depletion model. Error bars indicate range of 0.75 $v_d$ to 1.25 $v_d$.

The diffusion coefficient $\sigma_z$ was estimated from the near-surface concentrations of the nondepositing tracer. For each arc, the wind speed and $\sigma_z$ were determined by an iterative process: the wind speed was determined at a height 0.53 $\sigma_z$ by interpolating the detailed wind profiles measured on the 1600 m arc, and $\sigma_z$ was determined from the crosswind-integrated $SF_6$ concentrations by inverting Eq. (1). Where required by the models, $\sigma_z$ was estimated between measurement arcs by logarithmic interpolation, and a linear extrapolation was made from the value at 100 m to a value of zero at the release point. The pair of values obtained, u and $\sigma_z$, were used in the models, and their predictions were compared with those using the pair of values obtained from choosing the mean wind speed to be u(z = 2 m) and solving for $\sigma_z$. The latter choice is certainly an extreme case, since it is quite unreasonable to suppose that the mean transport speed of the plume is limited to the value of the wind speed at the release height; despite this, the maximum effect was less than a 13% decrease in one predicted value of $C_d/C_o$ for the corrected source depletion model.

We also attempted to extract values of $\sigma_z$ from the measurements of the $SF_6$ concentrations on the towers at 1600 m. The agreement with values obtained from using crosswind integrated concentrations, as described above, was poor. In some cases, $\sigma_z$ from one tower differed from $\sigma_z$ at the other tower by an order of magnitude. It was clear that a Gaussian distribution was not a good general descriptor for the vertical concentration profile. However, since the PAL-DS model is formulated in those terms, it seemed reasonable to choose a value for u and $\sigma_z$ that was consistent with the values of the crosswind integrated concentrations.

The height of the deposition surface is also unknown, since the terrain over which the tracer releases were carried out has vegetation of various types, ranging in height from about 10 cm to greater than 1 m. The effect on the wind profiles was to produce a displacement height of approximately 1.4 m. While the deposition is unlikely to occur at such a height, it is not obvious that it occurs at z = 0. Fortunately, the effect of varying the deposition height is quite weak; changing this height from 0.0 to 0.5 m resulted in a maximum change in the ratio $C_d/C_o$ of 7%.

The settling velocity is also required in all of the models except for the source depletion model, but this quantity is not known and is not expected to be a constant. Because ZnS tracer is a polydispersed tracer, the effective settling velocity will change as a function of distance from the source. These changes were studied with simulations of plume depletion using the PAL-DS model applied to several assumed size distributions for the ZnS. The settling velocity was not especially sensitive to the particular size distribution studied, at least for distances beyond the first 100 m or so. A value of 0.5 cm/s was chosen as an average, representative value for $v_s$, and the models were run using this value in a "base" case. When runs were also made with $v_s$ equal to 0 and 1.0 cm/s, the changes in $C_d/C_o$ were found to be 15% or less in all cases.

For each of the preceeding sensitivity tests, the statistical comparisons of the model predictions with the observations were recalculated. In all cases the relative performance of the four depletion models was unchanged.

It is also interesting to compare the measured deposition velocities with the averaged deposition velocities predicted by the PAL-DS model applied to a polydispersed tracer. Given an assumed distribution of particle sizes, the PAL-DS model can be run for a collection of size classes. The deposition velocity for each size class can be calculated by using a formula proposed by Sehmel and Hodgson (1980), based on a series of wind tunnel measurements. These results can then be summed to give weighted, averaged deposition velocities for the plume. Figure 8 shows results for three assumed size distributions denoted by $(d,\sigma_g)$, where d is the mass mean diameter, $\sigma_g$ the deviation of the logarithms of the particle diameters about the mean, and the modeled values of $\bar{v}_d$ were obtained from the Sehmel and Hodgson (1980) formula. The values of $\bar{v}_d$ at 1600 m have been chosen for the measured values. For the larger deposition velocities, the larger size distributions appear to give somewhat better agreement with observations, but the converse is true for the smallest values of $\bar{v}_d$.

It should not be surprising that a model for $\bar{v}_d$ based on wind tunnel data yields differences from observed values of $\bar{v}_d$ of a polydispersed tracer released over a plant canopy in the field. It is perhaps remarkable

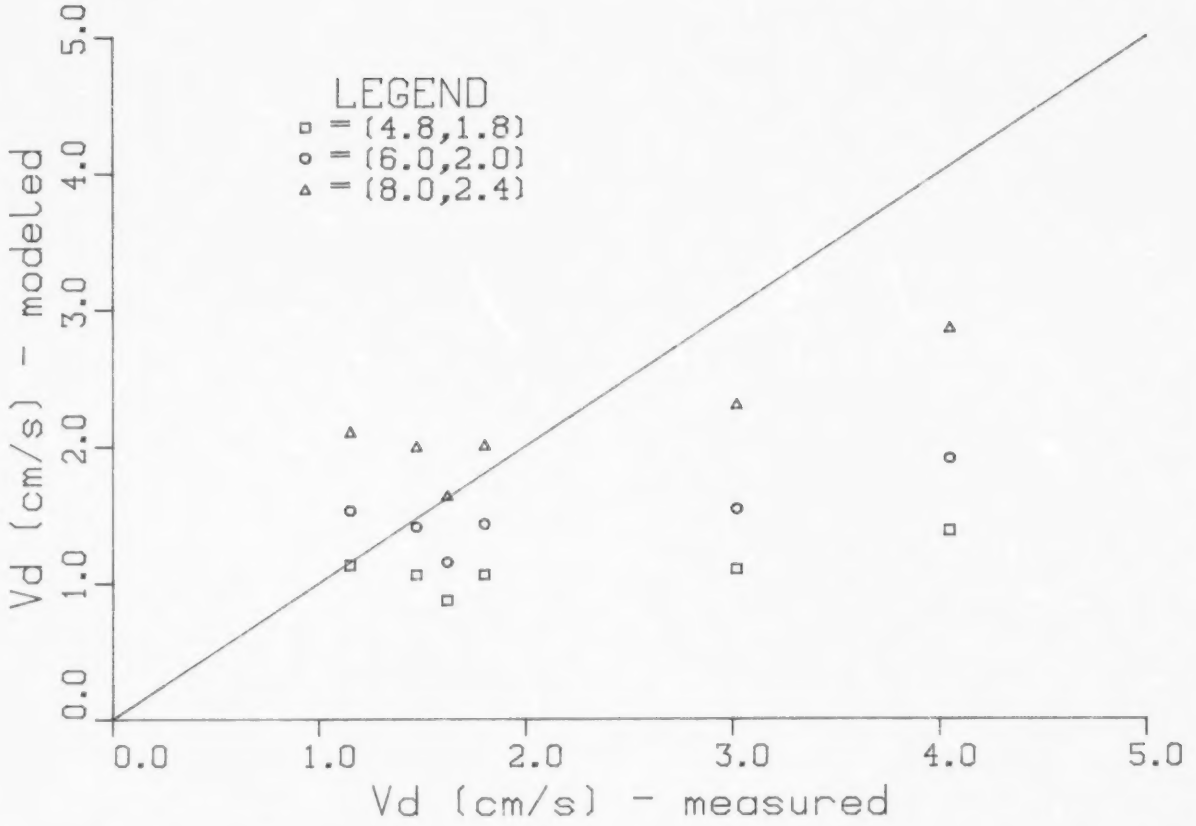


Figure 8. Comparisons of predicted and observed effective deposition velocities for a polydisperse tracer. Line indicates perfect agreement.

that the agreement is as good as it is; it provides us with some confidence that we are not making gross errors in our estimates of quantities dependent on size distributions, e.g., non-isokinetic correction factors for the ZnS concentrations (cf. Volume 1) or settling velocities.

## EXPERIMENTAL DESIGN

The adoption of the surface depletion technique to obtain deposition velocities to be used in an evaluation of the PAL-DS or other models raises two major questions: 1) can a polydispersed tracer such as ZnS be used to test the PAL-DS model predictions when the measurements do not distinguish between differing behavior for various particle sizes, and 2) if such a tracer can be used, can the effective deposition velocity be effectively determined using concentration measurements at only 5 arcs?

The answer to the first question is yes, if the effective deposition velocity deduced from the surface depletion approach produces the same values of $C_d/C_o$ for a monodispersed tracer as that observed for the polydispersed tracer. However, larger particles dropping out faster than smaller ones will produce an effective deposition velocity that is a function of distance. This effect is shown in Figure 9, in which the depletion of tracers with several size distributions, $(\overline{d},\sigma_z)$, was simulated by the PAL-DS model. The effective deposition velocity is a weighted average between the source and the downwind distance at which one computes C. Thus, in comparisons with simulated monodispersed particle behavior, a different deposition velocity must be used for each downwind distance at which $C_d/C_o$ is to be determined.

A number of numerical experiments were conducted to test this hypothesis, using several assumed size distributions for the ZnS. The polydispersed and monodispersed concentrations were virtually identical for the range of meteorological conditions encountered during our field tests. Discrepancies could occur when settling of the large articles near the source caused them to reach the surface well before the remainder of the plume was diffused there. Under such circumstances the deposition velocity varies rapidly with distance. A rough criterion for the polydisperse and monodisperse concentrations to agree within 10% is that the mass fraction

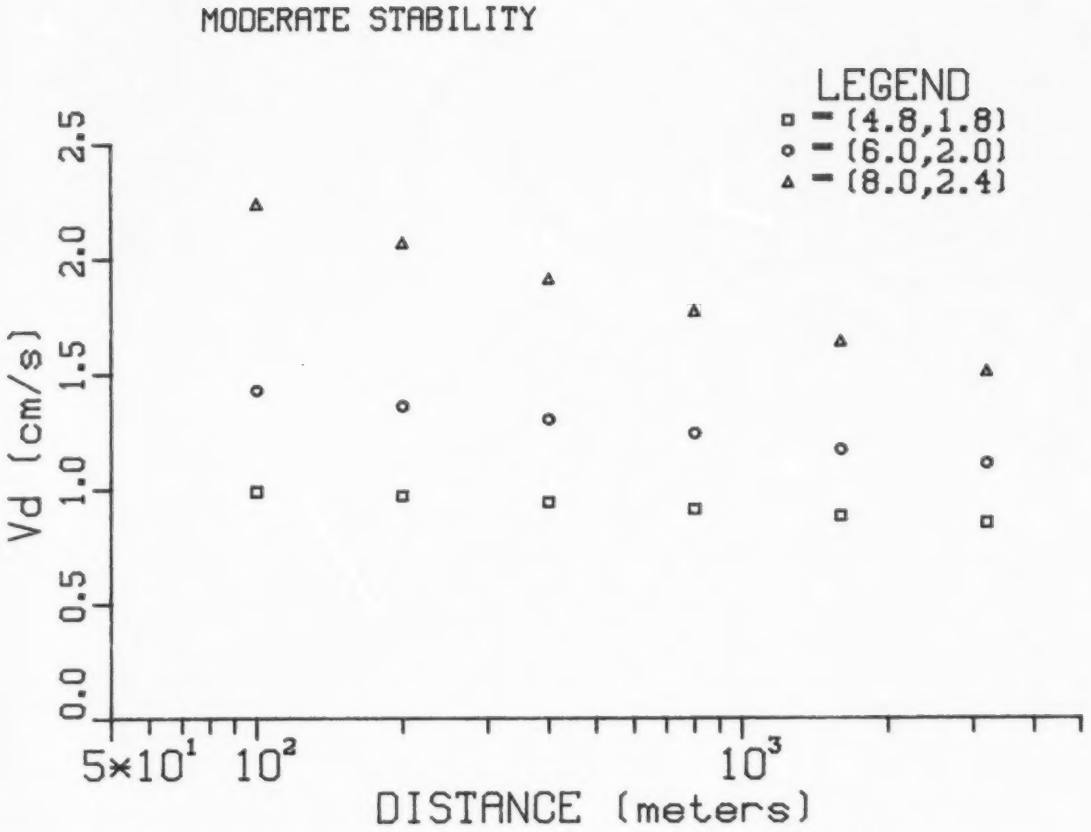


Figure 9. Calculated variation of deposition velocity with distance for three size distributions and moderate stability. Numbers in parentheses refer to mass mean diameter and deviations of logarithms of diameters about the mean.

of particles with settling velocities exceeding $u\sigma_z/x$ (near the source) be less than about 15%; these conditions were easily met in our field tests. Thus, the polydispersed nature of the ZnS tracer should not be a major problem in this analysis.

The second question is concerned with the adequacy of sampling $C_d$ and $C_o$ at only 5 arcs (100, 200, 800, 1600 and 3200 m from the release point) to obtain $\bar{v}_d$. An examination of the form of the integrand of Equation (11) is helpful in this regard. Figure 10 shows the calculated behavior for this integrand as a function of distance x' for a value of x = 1600 m, assuming moderately stable conditions and a deposition velocity of 2.5 cm/s. The symbols are the calculated points, and the line is found from logarithmic interpolations between the successive arcs. The interpolations give a good approximation to the integrand; thus, it is reasonable to suppose that concentration measurements at a limited number of arcs will give acceptable estimates of $\bar{v}_d$.

To test this further, we generated values of $C_d$ and $C_o$ for deposition velocities ranging from 1 to 5 cm/s for monodispersed particles. The surface depletion model was used to produce these "experimental" data, assuming D, E and F Pasquill stability classes and Gaussian diffusion in the vertical. The algorithm used to extract $\bar{v}_d$ from the experimentally determined values of $C_d$ and $C_o$ was then applied to the generated values. In all cases the deposition velocity computed at 1600 m and 3200 m from the values of $C_d$ and $C_o$ at the 5 arcs agreed with the actual deposition velocities within 4% or better. If the diffusing plumes behave in some pathological fashion between the arcs, large errors could be introduced, but this seems implausible. Thus, determination of $\bar{v}_d$ in this fashion should not be a limiting factor in an evaluation of the PAL-DS model.

## ACCURACY OF MEASUREMENTS

Volume 1 of this report provided a discussion of the accuracy to which various measurements could be made. Clearly, an assessment of model performance must take into account the uncertainties that measurement errors and limitations impose. It is difficult to quantify many of these

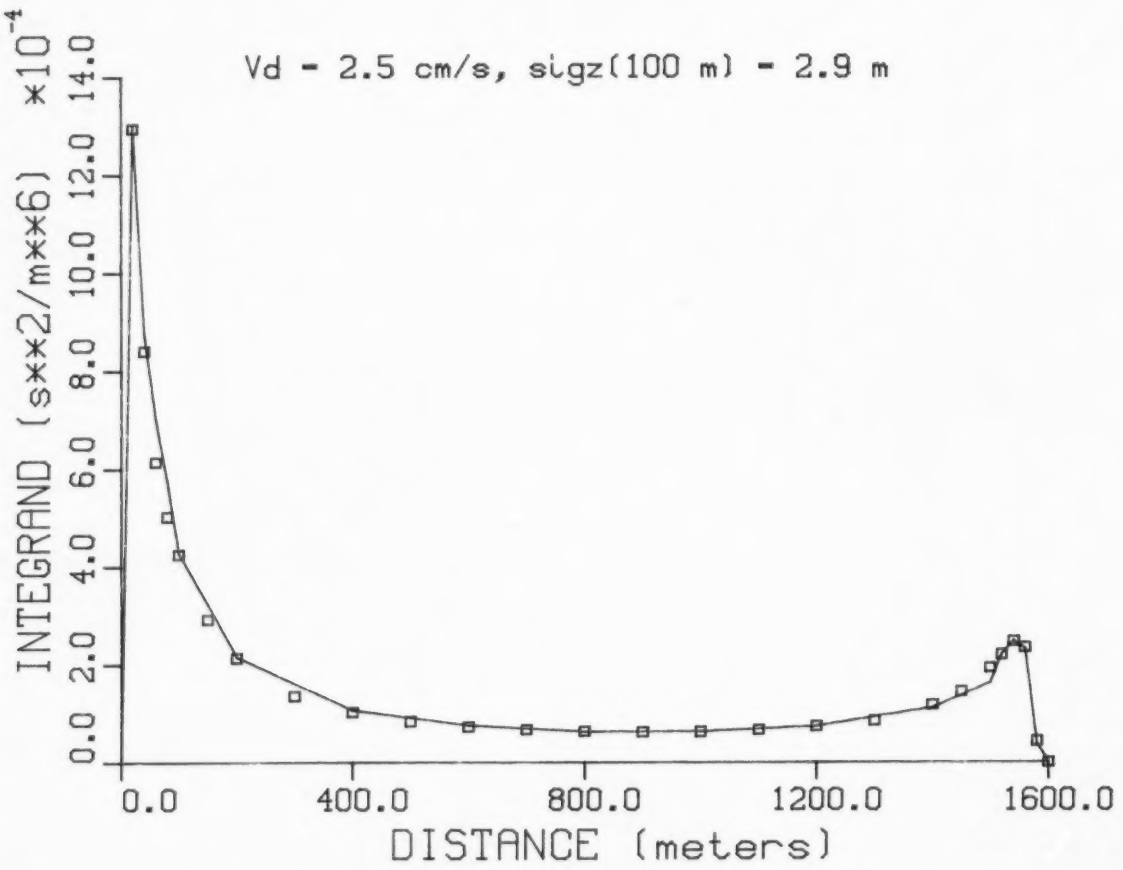


Figure 10. Comparison of values of convolution integrand (squares) and approximation used in algorithm for evaluating integral (solid line).

factors, but some general observations can be made that may prove useful in the interpretation of our model evaluations.

Measurement errors, of course, can be either random or systematic. The estimation of crosswind integrated concentrations from individual concentration values is expected to exhibit random errors, assuming the tracer concentrations themselves are not systematically wrong. The various statistical tests that we have described, and inspection of the results in Figures 1-4 imply a clear superiority of the corrected source depletion model in the prediction of $C_d/C_o$ ratios, assuming that measurement errors are random in nature. Systematic errors are more serious. We have already described the sensitivity of the models to various changes in the input parameters; effects of changes in $\bar{v}_d$ are probably the most serious and should be considered in greater detail.

Perhaps the most obvious possible source of error in the estimation of $\bar{v}_d$ is a systematic error in the concentration measurements of ZnS. In Volume 1 we noted that the calibration constant for determining ZnS concentrations from the fluorescent counting device known as a Rankin counter had a standard deviation of about 25% of the mean. Also, a nearly identical mean value for the constant had been obtained in a previous, independent series of measurements, so the associated uncertainty may be somewhat smaller than 25%.

The corrections to the ZnS concentrations to account for nonisokinetic sampling introduce yet another difficulty. Sehmel (1966) obtained estimates of these correction factors based on a particular assumed size distribution. Because recent sizing studies (cf. Volume 1) gave differing estimates for the size distribution of ZnS, this issue cannot be considered resolved . Fortunately, the wind speeds during the tracer releases were generally light and the flow rates for most of the filters were as high or higher than in previous Hanford tracer studies with ZnS (Nickola, 1977). This combination of factors results in decreased sensitivity to nonisokinetic sampling errors, and uncertainties in the correction factors on the order of 5% are probably reasonable. The effects of systematic errors in ZnS concentrations can be studied to some extent by considering a rather simple analysis. Recall that the average deposition velocity at x was determined from the expression

$$\bar{v}_d = \frac{\int_0^x v_d(x')C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'}{\int_0^x C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'}$$

$$= \frac{C_o(x,z_d,h) - C_d(x,z_d,h)}{\int_0^x C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'} \quad . \qquad (18)$$

Let us assume that at all distances, the concentrations $C_d$ are in error by some constant factor. In particular, assume that the measured value of $C_d$ is related to the true value by $C_d$ (measured) = f $C_d$ (true). Then (18) becomes,

$$\bar{v}_d \text{ (meas)} = \frac{C_o(x,z_d,h) - f\ C_d(x,z_d,h)}{f\int_0^x C_d(x',z_d,h)(1/Q_o)C_o(x-x',z_d,h=0)dx'} \qquad (19)$$

Here, $C_o$ and $C_d$ denote true concentration values, while $\bar{v}_d$ (meas) is the measured deposition velocity. The true deposition velocity would be recovered if f were equal to 1. Finally, assume that at some distance of interest, e.g., 1600 m, $C_d$ is some fraction y of $C_o$, i.e., $C_d = yC_o$ Then one can show that the ratio of measured deposition velocity to true deposition velocity, R, is given by

$$R = \bar{v}_d(\text{meas})/\bar{v}_d(\text{true}) = (1 - yf)/\left[f(1-y)\right] . \qquad (20)$$

If $f < 1$ then $R > 1$, and the measured deposition velocity will be larger than the true value. The models will then tend to predict ratios of $C_d/C_o$ that are too small, thereby compensating for the systematically low measurement of $C_d$ in the first place. The degree of compensation will depend upon the particular model and the atmospheric stability, but there is at least some tendency for the data to be self correcting.

An example may help illustrate this effect. From the release of June 5, 1983, $C_d/C_o$ was 0.40, while the corrected surface depletion model predicted a value of 0.43. If f = 0.85, R = 1.33, and the derived value of

$\bar{v}_d$ was 33% too large. If $\bar{v}_d$ is reduced to its true value, the model then predicts a $C_d/C_o$ of 0.53 while the true concentration ratio becomes 0.40/0.85 = 0.47. Similarly, the PAL-DS model predicted a value for $C_d/C_o$ of 0.61 from the original data; with the reduced value of $\bar{v}_d$ the new prediction is 0.69.

Thus, systematic errors in $C_d$, reflected in the derived values of $\bar{v}_d$, can lead to changes in model predictions and relative performance. However, the consequences for relative model performance are not nearly as significant as one might suspect from simply looking at the sensitivity of the models to variations in $\bar{v}_d$. It seems unlikely that the systematic biases found for some of the models (cf. Section 7) would be seriously altered. There is still the possibility that some other, fundamental error is made when we deduce effective deposition velocities from the convolution integral arising from the surface depletion approach. A rigorous test of the surface depletion model would be a major project in itself, and perhaps is not economically feasible with current tracer technology. Nonetheless, the relative ordering of the models' biases, which are generally in keeping with theoretical expectations, lends additional support to to our belief in the basic consistency and correctness of our model evaluations.

## SECTION 9

## DIFFUSION METEOROLOGY

In predicting actual plume concentrations, the consequences of uncertainties in the diffusion meteorology are probably far more severe than the consequences of choosing one deposition model over another. This can be seen by examining the performances of the models discussed in this report and comparing their faithfulness to the data with that of various diffusion models (e.g., Irwin, 1983). In the interest of completeness, we have examined some factors affecting plume dispersion and compared actual dispersion parameters, determined with the tracers, with various predictions.

Figure 11 compares the values of $\sigma_y$ measured or estimated at each arc and the values expected from empirically determined relationships between $\sigma_y$ and $\sigma_\theta$, the standard deviation of the horizontal wind direction at the release height (Doran et al. 1978). The agreement is rather poor, with the predicted values overestimating the actual values in almost all cases. Figure 12 shows comparisons of "measured" $\sigma_z$, i.e., values obtained from the crosswind integrated concentrations of $SF_6$ and an assumed Gaussian distribution in the vertical, with values predicted by the Lagrangian similarity theory of Horst (1979). Again, the agreement is rather poor, with the theory generally underpredicting the "observed" values. We do not have a good explanation for these discrepancies, but they do underscore the problems associated with using "standard" micrometeorological parameters to estimate the diffusion of a plume.

The four plume depletion models we have evaluated do show systematic differences in their behavior. These differences are small, however, compared to the effects introduced by possible errors in the description of the diffusion meteorology. If these diffusion meteorology errors are random, then the choice of the deposition model to use may be more significant, but the statistical variability in the diffusion is apt to be the controlling factor. Nevertheless, the corrected source depletion model and the mass-conserving version of the PAL-DS model are not significantly

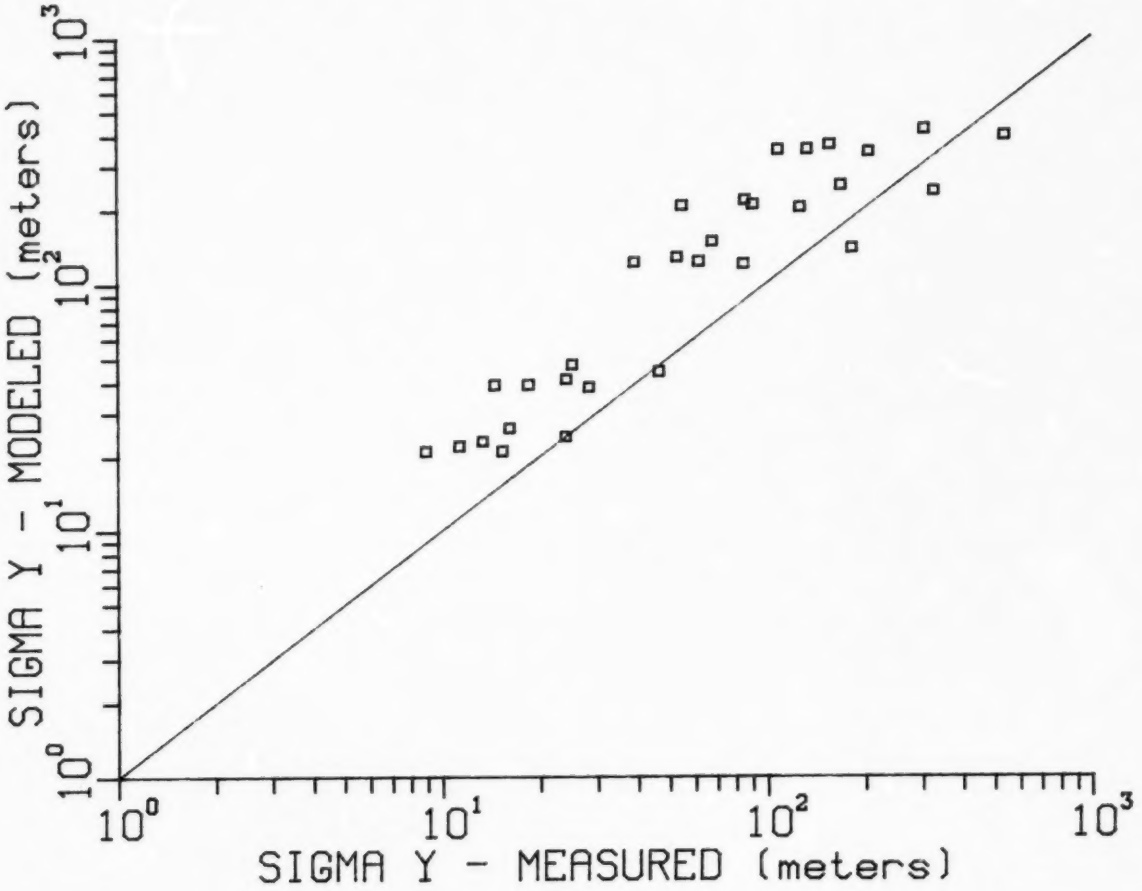


Figure 11. Comparison of observed $\sigma_y$ and calculated $\sigma_y$ based on values of $\sigma_\theta$.

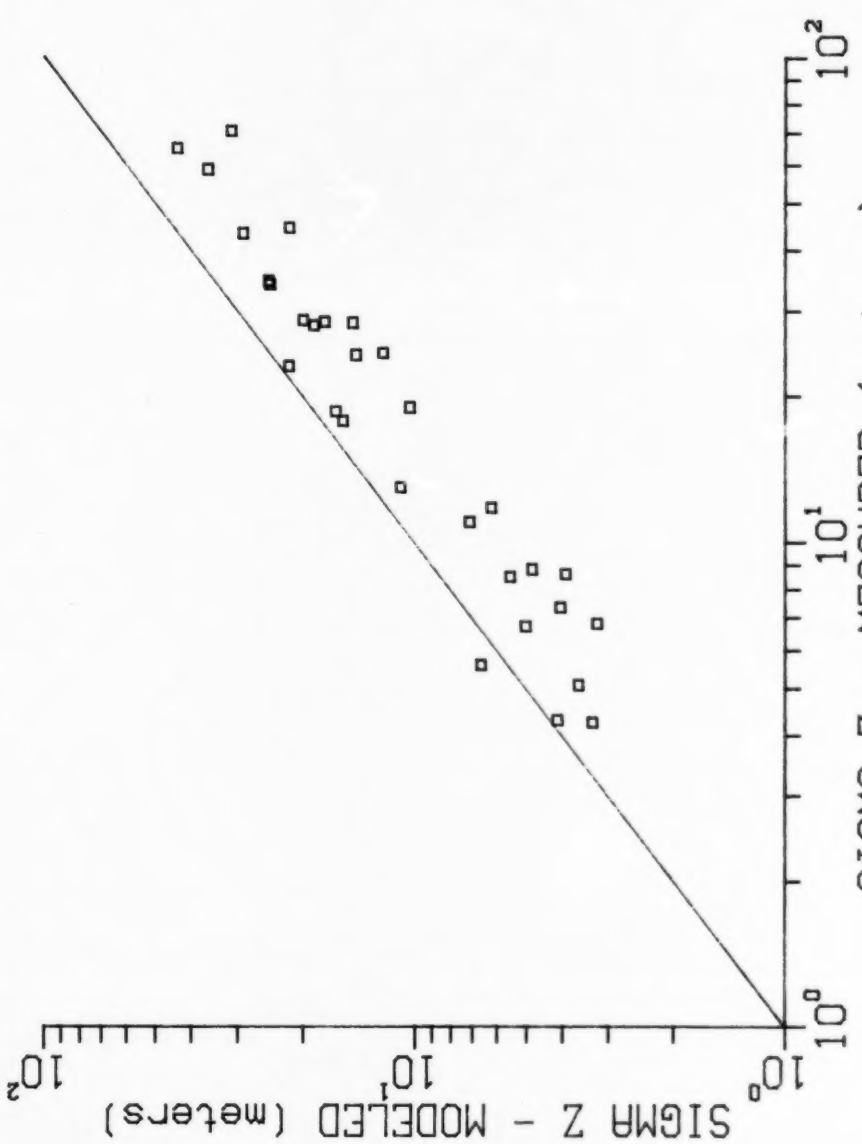


Figure 12. Comparison of observed $\sigma_z$ determined from crosswind-integrated concentrations calculated from Lagrangian similarity theory.

more difficult to apply than the PAL-DS model, and we recommend that they be used instead. We base this recommendation on two aspects of our analysis: 1) the data, albeit subject to some uncertainty, imply the superiority of the corrected source depletion and the mass-conserving PAL-DS models, and 2) the theoretical bases for the two recommended models appear to be better than for the other two.

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